Experimental and theoretical study on asymmetric carbon contamination growth on SFET-exposed mask

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Introduction: Impact of mask contamination

- EUV Mirror
  - Throughput loss
  - Degradation of optical performance

- EUV mask
  - Throughput loss
  - CD change
  - Exposure latitude loss

Contamination control technology
  - Mitigation & Prevention
  - Cleaning

Focus of this work is Topography of carbon contamination grown on the SFET and EUV1 exposed masks, and its modeling

Introduction: Impact of Mask contamination

Carbon contamination cause the CD change as well as Throughput loss

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The impact depends on the topology of carbon coverage on mask surface.
Without the deposition on the sidewall, drop of the intensity threshold is the same as the multilayer reflectivity.

- Carbon density 1.3 g/cm³
**Motivation:** CD-SEM Observation of SFET Exposed mask suggests asymmetric carbon growth

Vertical Illumination to pattern

Parallel illumination to pattern

Non-Contaminated Area

Contaminated Area

White-band width asymmetry

Right-side WBW is wider than left-side one. (5nm)

WBWs are almost same.

CD Increase (20 nm)

Suggests growth on side wall

White band width of sunshine side wall was significantly wider than sunshade one.
**Motivation:** Asymmetry of white band width depends on ring-field position in EUV1 exposed mask

In-field position dependence of EUV1 illumination direction

Azimuthal dependence was observed in white band width

**Observed position on mask**
Pattern profile observed by 3D-AFM

Contaminated area

Clean area

Tip Shape removed from Image

hp 22 nm / azimuth 90 deg

SFET QC Mask

cf. raw profile

contaminated

clean

Veeco InSight 3DAFM
Purpose of this work

1. Make clear the accurate topography by TEM observation.
   - SFET Mask: illumination dependence
   - EUV1 Azimuthal angle dependence

2. Understand the mechanism by theoretical calculation.
   - Model;
     I. Reaction limit & Geometric optical model
     II. Supply Limit Model
     III. Electric field strength Model
   - Comparison with TEM observation
   - Simulation of printed image of contamination mask based on the actual TEM image
TEM observation of SFET Exposed Mask

Carbon contaminated LR-Ta/TaBN/Cr mask (22 nm hp)

Asymmetry was observed clearly in the perpendicular illumination

Bottom thickness is thicker than top and side walls
Model 1: Reaction limit & Geometric optical model

Model Calculated result

Carbon grows primary on EUV irradiated area, top and bottom, even when secondary electron induced growth is considered.

Conformal-like coverage cannot be explained by this model.
Model 2: Supply Limit Model

Top thickness is thicker than bottom one.

This model cannot explain the observed asymmetry.
Model-3: Electric Field Strength model

Calculation of contamination coverage based on electric field calculation

**EM-field calculation**
- Mask structure
  - Maxwell equation
    - Spatial distribution of electric field strength
- EM-suite

**Topography calculation**
- Mask structure
  - Growth rate calculation
    - String model
  - Topography calculation
- Original program
Calculation of Electric field strength ($E^2$) by EM-suite software

22 nm l/s
EUV; parallel to pattern

22 nm l/s
EUV; vertical to pattern
Calculated result
6 deg irradiation to pattern

Condition; 22 nm dense LS, irrad. angle = 6 deg,
Growth Model; growth rate $\propto E^2$, coverage change = String model

Approximately conformal coverage was reproduced.
Asymmetric coverage was reproduced. There remains discrepancy in sunshade wall thickness
Threshold Change by Contamination

![Graph showing relative reflectivity/threshold change with film thickness and contamination.](image)

- Relative Reflectivity / Threshold
- Actual Contamination
- Thresholds at Center of ED Window
- Conformal Deposition

Film Thickness (nm): 0 5 10 15 20

Reflectivity of Mirror

20 nm
Pattern Shift by Asymmetric Deposition

Intensity (arb. units)

Position (nm)

Clean
Contaminated

hp 22 nm Iso ⊥

CD 22 nm

Pattern shift by contamination deposition

-0.21 nm

Cf. Conformal deposition:
+0.01 nm for 10 nm, +0.08 nm for 12 nm-thick
Summary (1) Contamination topography

1. Optical simulation reveals that impact of contamination is Conformal deposition > Top & Bottom deposition
2. Model contamination formed by synchrotron radiation (parallel to pattern) shows Approximately conformal coverage
3. Actual contamination of SFET exposed mask:
   - CD-SEM observation shows white-band width difference (Sunshine side > Sunshade side)
   - 3D-AFM observation shows Thickness on space bottom > Thickness on absorber top
4. Actual contamination of EUV1 exposed mask
   - In addition to SFET observation, Azimuthal dependence was observed in CD-SEM white band width
Summary (2) TEM observation

Topography of carbon contamination formed on SFET exposed EUV was measured by TEM. The results reveals

1. In parallel irradiation case,
   Approximately conformal coverage was observed.
   Significant thickness difference was observed;
   Bottom > side \(\cong\) Top
   Overhang structure was found in side wall.

2. In perpendicular irradiation case
   Asymmetric coverage was observed;
   Sunshine wall thickness > Sunshade wall thickness
   Overhang structure was outstanding in sunshade side wall.
Summary (3) Modeling & Simulation

[1] Simple geometric-optical model cannot reproduce the conformal-like coverage observed in model contamination even in taking a secondary-electron-induced growth on opposite-wall.

[2] Supply limit model cannot reproduce the asymmetry observed in perpendicular illumination case.

[3] Integrated model of electric-field-calculation and string-model-calculation reproduces
   • conformal-like coverage in the case of parallel illumination
   • asymmetric growth on sidewall in the case of perpendicular illumination.
   • differences in growth rate on absorber top and space bottom

The results of Model 3 calculation agrees well with TEM observation in parallel illumination case, but shows slight difference in perpendicular illumination case.